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SEMI-ANNUAL PROGRESS REPORT

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to

National Aeronautics and Space Administration

on

NASA Grant NSG-3264

Entitled

"THE BOUNDARY LAYER ON COMPRESSOR CASCADE BLADES"

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A. INTRODUCTION

The purpose of NASA Research Grant NSG-3264 is to characterize the flow field about an airfoil in cascade at a Reynolds number of 5×10^5. The program is experimental and combines hot wire and laser anemometry with flow visualization techniques in order to obtain detailed flow data (e.g., boundary layer profiles, points of separation, and the transition zone) on a cascade of relatively highly loaded blades. The information provided by this study is to serve as benchmark data for the evaluation of current and future predictive models, in this way aiding in the compressor design process.

NASA Grant NSG-3264 is envisioned as a four year program. During the first year, the feasability of the proposed research is to be demonstrated by successfully testing both the experimental techniques and the data acquisition/reduction system. In the second year, these techniques are to be applied to define the flow field over a relatively heavily loaded airfoil in cascade. In subsequent years, the influence of variation of incidence angle and turbulence intensity are to be assessed.

This report summarizes the second year's research activity for the period 1 June 1981 to 1 December 1981. Progress made from 1 June 1979 to 1 June 1981 was presented in References [1-4].

B. INITIATION OF PROGRAM

NASA Grant NSG-3264 was initiated on 1 June 1979. A six month contract extension, to account for a change in principal investigators, was granted effective 31 May 1980. The contract is currently approximately six months behind schedule. This delay was caused by the much longer than anticipated time required to fabricate new cascade blades and the inadvertent disruptions caused by the addition of an extension to ARL's Garfield Thomas Water Tunnel Building.

Third year funding was received in November 1981.

C. PROGRESS IN THE PERIOD 1 JUNE 1981 TO 1 DECEMBER 1981

1. Rationale for the Test Program

As reported in Reference [4], some redesign of the cascade facility, for the purpose of incorporating the requirements of the LDA system into the design was necessary. Of particular importance was the intended use of a combination of suction upstream of the blade pack with diverging blade pack walls, as opposed to blade pack suction alone, for spanwise two dimensionality control.

The use of diverging walls in combination with upstream suction to control two-dimensionality was felt to be novel enough in cascades to warrent testing the concept separately. In addition, such tests would be useful in providing both the data by which to make operational the required data acquisition and reduction systems and the experience necessary to develop cascade testing procedures while the new double circular arc blades (DCA4) were being fabricated.

To this end the cascade testing was divided into two phases. In Phase I, it was intended to redo some of the cascade tests reported in Gearhart and Ross [5,6] with combination suction and diverging walls replacing blade pack suction alone. Results of these tests are reported in Section C.2.

Phase II involves the detailed cascade testing and boundary layer measurements on the new double circular arc blades. Preliminary cascade testing has begun and some results are given in Section C.3. A detailed presentation of these results will form the basis of Mr. R. Moyer's M.S. paper and will be presented to NASA, in the near future, as an interim report.

2. Cascade Tests With ARL* Blading

An ARL blade, extensively tested in Reference [6], was used for the Phase I tests. Figure 1 shows a comparison between this blade section and the NACA 65-($8A_2I_{8b}$)10 blade. An attempt was made to match a condition tested in Reference [6] for the Phase I test; that is

$$\beta_1 = 45°$$

$$\sigma = 2.108$$

$$\alpha_i = 15.25°$$

$$\text{and } i = -4°,$$

where, following Gearhart and Ross [6], β_1 is the angle between the flow and axial directions, σ is the solidity, α_i is the angle between flow direction and the blade chord and i is the incidence angle. Subsequent to these tests, more precise position measurements, using a gunners sight, indicated that

$$\alpha_i = 17.1°$$

$$\text{and } i = -2.15°$$

The Phase I cascade tunnel configuration is shown in Figure 2. Inlet velocity, W_1, was measured with a standard pitot static probe located approximately as shown. It is worth noting here that this inlet position, downstream of the suction duct, is a more accurate measure of W_1, then it is possible to achieve with blade pack suction. The flow direction was made parallel to the splitter plate (itself level to the floor) by using an adjustable dump (as shown on Figure 2), while sensing flow direction with a prepositioned wedge probe attached in a streamlined manner to the splitter plate.

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*ORL in References [5,6].

Velocity surveys of the inlet and outlet flow were performed using two calibrated five hole probes. These probes are capable of resolving the three components of velocity as well as the relative yaw and pitch angles [7]. Blade static pressure measurements were made on the central instrumented blade. These measurements could be made at the blade mid-span as well as approximately 3 1/8-inches to the right and left of mid-span.

As before [3], all pressures were measured using a Validyne Model DP15 (±0.5 psia) pressure transducer, powered and conditioned by a Validyne Model CD15 Carrier Demodulator. The pressure transducer was calibrated against a Merrian micromanometer. Recording of multiple pressures was facilitated by the use of a Scanivalve Model 24C4121-024 switching system. All velocities were corrected (as in Reference [3]) for temperature and barometric pressure.

All readings were recorded on paper tape to be processed at a later time on ARL's IBM System 7. This data was then transferred to the ARL IBM System 34 for reduction. Significant plots, such as the blade pressure distribution, could be made on the ARL Calcomp 748.

Boundary layer suction was provided on the side walls through 1-inch x 26-inch porous suction slots which were manifolded and connected to a General Electric 10 HP centrifugal blower. Top suction was provided by a Buffalo Forge 5 HP centrifugal blower. Blower power and thereby suction rate could be varied* by use of an inverter [Borg-Warner Model BW 1200 Accuspede Drive].

Interpretation of cascade test results is greatly facilitated if, for uniform inflow conditions, two dimensional flow exists in the cascade. Criteria for two dimensionality has been thoroughly defined in Reference [8], and roughly speaking, its existence insures that the flow closely approximates that which would exist in a cascade consisting of an infinite number of blades, equally spaced, with each blade of infinite spanwise extent. A simple set of criteria used for a first run through here is that,

1. equal pressures, velocities and directions exist at different spanwise locations

and 2. the average axial velocity is the same at both inlet and exit.

Initially one must insure that the inlet flow is uniform. This was accomplished in Reference [5] by showing the equality of eight static pressure taps located on both side walls approximately one chord length upstream of the blades. A similar approach was attempted in the current work, but with no success. The difficulty was traced to the sensitivity of the static pressure probes to alignment coupled with the inability to align them flush with the inside plywood walls. As this is a convenient method to determine inlet uniformity, much greater care in installing these taps will be exercised with the DCA4 blades.

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*The actual suction rate was not measured.

Inlet uniformity, then, was determined here from both velocity traverses using wedge, five hole and pitot-static probes and from comparisons among centerline and off-center pressure taps on the instrumented blade.

A typical plot of the inlet velocity profile just upstream of the splitter plate is presented in Figure 3. In Figure 3, W_2 is measured with a five hole probe, which is traversed vertically in half inch increments, while W_1 is from a stationary pitot-static probe. The mean value of W_2/W_1 over the 13-inch traverse is 1.0099, with a standard deviation of 0.0107, which compares quite favorably with the predicted value of 1. A typical horizontal traverse using a wedge probe located one chord length upstream of the blades (and suction) at the center of the test section is shown in Figure 4. Here the velocity is 108.24 ft/sec with a standard deviation of 0.18 ft/sec over an eight inch core. The effect of suction on the side wall boundary layer will be discussed later. It should be noted here that calibration indicates that the wedge probe reads roughly 3% higher than a standard pitot static probe, at these velocities.

In Figure 5, additional evidence of spanwise uniformity is presented through a plot of c_p distribution on the pressure surface of the instrumented blades, both at centerline and 3 1/8 inches to the left and right of centerline. In Figure 5

$$c_p = \frac{P_\ell - P_\infty}{1/2\ W_1^{\ 2}}$$

where, P_ℓ is the local blade static pressure, P_∞ is the upstream static pressure and W_1 is the approach velocity. Here both P_∞ and W_1 are taken from a pitot-static tube mounted in the free stream 3-inches upstream of the blade's leading edge in mid-passage above the instrumented blade.

A great deal of effort went into determining the effectiveness of diverging the blade pack walls on controlling two dimensionality. For the runs reported here, the outlet flow and angle were measured with a five hole probe located approximately 1 1/3 chord lengths downstream of the blade's trailing edge, while the inlet flow velocity was measured with the same standard pitot static tube at the same location as noted in the previous paragraph. The choice of 1 1/3 chord lengths was unfortunate in an absolute sense as the peaks and wakes of the exit profiles had a tendency to be "washed out" by that point, making precise interpretation difficult. Trends, however, were still discernable.

In the present experiments, the ability to reduce the exit to entrance axial flow ratio to one was used as a test of the wall divergence technique. A simple-minded analysis, which accounts only for the increase in displacement thickness over the blade pack indicates that a divergence of roughly 0.1 in/ft of blade pack wall should be adequate at these Reynolds number (3-4 x 10^5). In Figures 6 and 7 we examine the effect of wall divergence on the axial velocity ratio for two runs in which the turning angle β_2 was approximately the same at 29°. In Figure 6 there is no divergence and the axial flow ratio, averaged over one blade spacing centered on the instrumented blade, is 1.17. In Figure 7,

in which each wall is diverged 3/4-inch the axial flow ratio is 1.11. It should be noted here that for each of these cases there was neither side wall nor top suction. Blade Reynolds number was roughly 3.35×10^5.

The fact that only a 6% reduction in axial flow velocity ratio could be achieved with a divergence of 3/4-inch casts doubt on boundary layer growth as the major mechanism for the generation of low speed fluid near the walls. It seems likely from this data, that the most important mechanism for the spread of low speed fluid is the upstream blade-boundary layer interaction.

The need to eliminate blade-boundary layer interaction signalled the need for a close look at the effectiveness of the upstream suction. The porous side wall suction slots were constructed as noted in Reference [5]. Each suction slot was 1-inch x 26-inches and was located approximately 4-inches upstream of the blade's leading edges. The slots were manifolded and connected to a G.E. 10 HP centrifugal blower, as noted earlier. Initial attempts to use a 5 HP Buffalo Forge blower (as used in Reference [5]) for the side wall suction was not successful; resulting in 4-inch side wall "boundary layers" at 1 1/3 chord lengths downstream of the trailing edge. The effect of suction is shown in Figure 8 and 9. In each case half of the horizontal flow field (it was shown to be symmetric) was traversed using a 5 hole probe located approximately 4-inches downstream of the suction slot at about centerblade location. Figure 8 shows, with no suction a side wall boundary layer of approximately 1.75-inches at what is effectively the blade leading edge station, while in Figure 9, for maximum suction, all of the side wall boundary layer was removed. It is worth noting that exit surveys showed that for the conditions of Figure 8 a 4 1/2-inch side wall exit boundary layer results, while for maximum suction this boundary layer is reduced to 2-inches (at 1 1/3 chord lengths downstream of trailing edge).

To help define the peaks and wakes of the exit data more precisely the exit five hole probe was relocated at a position 1/2 chord downstream of the blade trailing edge plane. In Figure 10, the exit data for a configuration in which the simple criterion for two-dimensionality ($Wx_2/Wx_1 = 1$) was satisfied is presented. For the case shown, the walls were diverged 1/4-inch and both top and side wall suction are employed (not at maximum). The associated blade static pressure measurements are shown in Figure 11.

More detailed analysis of this data will follow in an interim report.

3. <u>Cascade Tests of the Double Circular Arc Blade, DCA4</u>

Preliminary cascade testing on the double circular arc DCA4 blades designed at NASA Lewis was begun. In Figure 12, static pressure distributions taken on the three central instrumented blades are shown. Note the discrepancies among the pressure distributions at the leading edge as well as at various other locations. These discrepancies have caused some concern, and currently both blade surface finish and side wall mounting consistency are being checked.

More detailed analysis of the work to date on the double circular arc blades will follow in an interim report.

D. RELOCATION OF THE CASCADE FACILITY

The cascade facility is being relocated at this time. It is anticipated that testing will resume by the end of January 1982. Initial testing will aim to re-establish the existence of a uniform, low turbulence entry flow.

References

[1] Deutsch, S., Semi-Annual Progress Report for NASA Grant NSG-3264, January 1980.

[2] Deutsch, S., Semi-Annual Progress Report for NASA Grant NSG-3264, June 1980.

[3] Deutsch, S., Semi-Annual Progress Report for NASA Grant NSG-3264, January 1981.

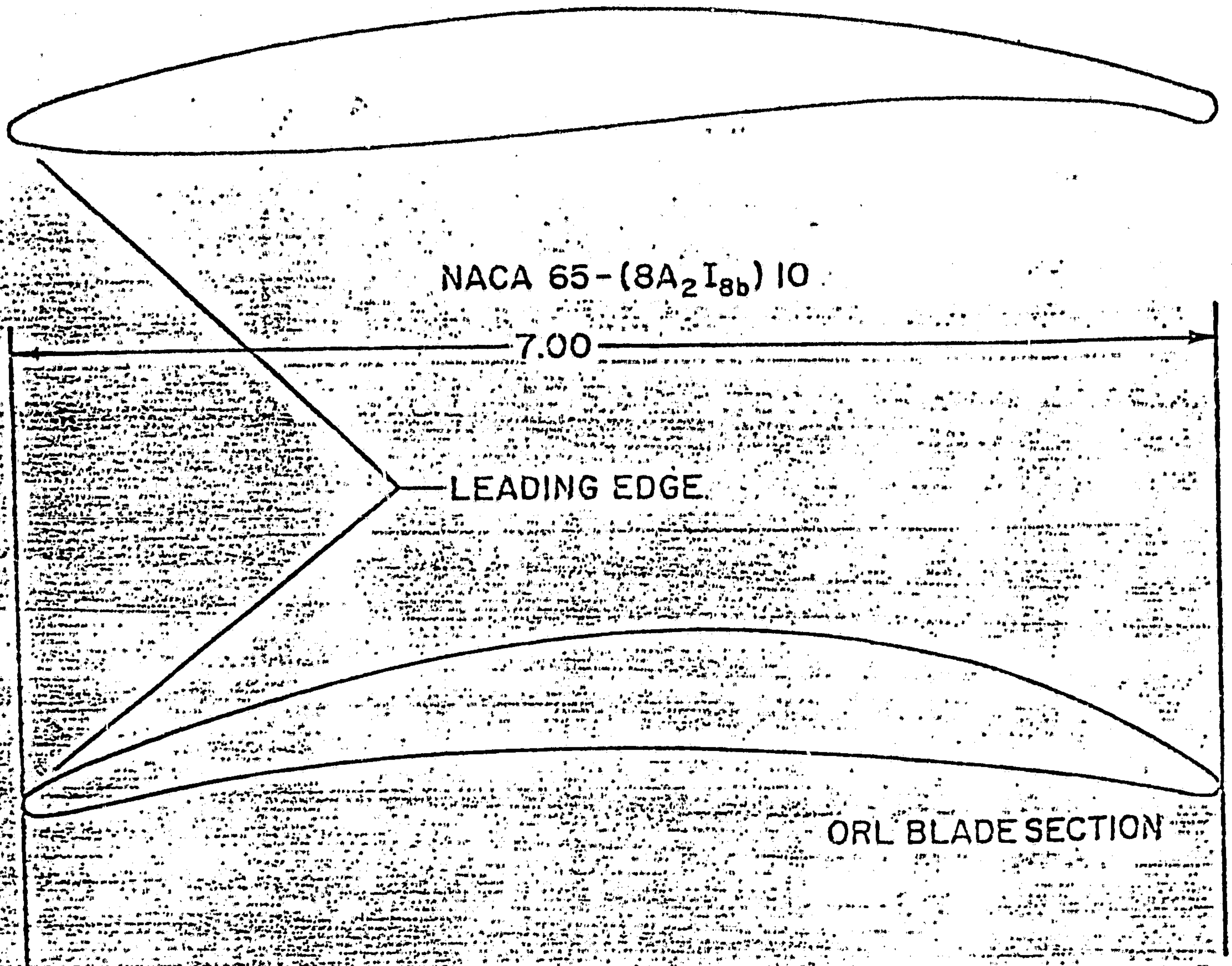
[4] Deutsch, S., Semi-Annual Progress Report for NASA Grant NSG-3264, June 1981.

[5] Gearhart, W. S. and Ross, J. R., "A Subsonic Cascade Test Facility-An Aid to Hydrodynamic Blade Design," ORL Internal Memorandum, File No. 506-02, March 13, 1970.

[6] Gearhart, W. S. and Ross, J. R., "Two Dimensional Cascade Tests of a Compressor Blade Designed by the Mean Streamlined Method," ORL Internal Memorandum, File No. 71-32, February 22, 1971.

[7] Treaster, A. L. and Yocum, A. M., "The Calibration and Application of Five Hole Probes," ISA Transactions, Vol. 18, November 3, 1979.

[8] Erwin, J. R. and Emery, J. C., "Effect of Tunnel Configuration and Testing Technique on Cascade Performance," NACA Report 1016, 1951.



COMPRESSOR BLADE SECTIONS

FIGURE 1

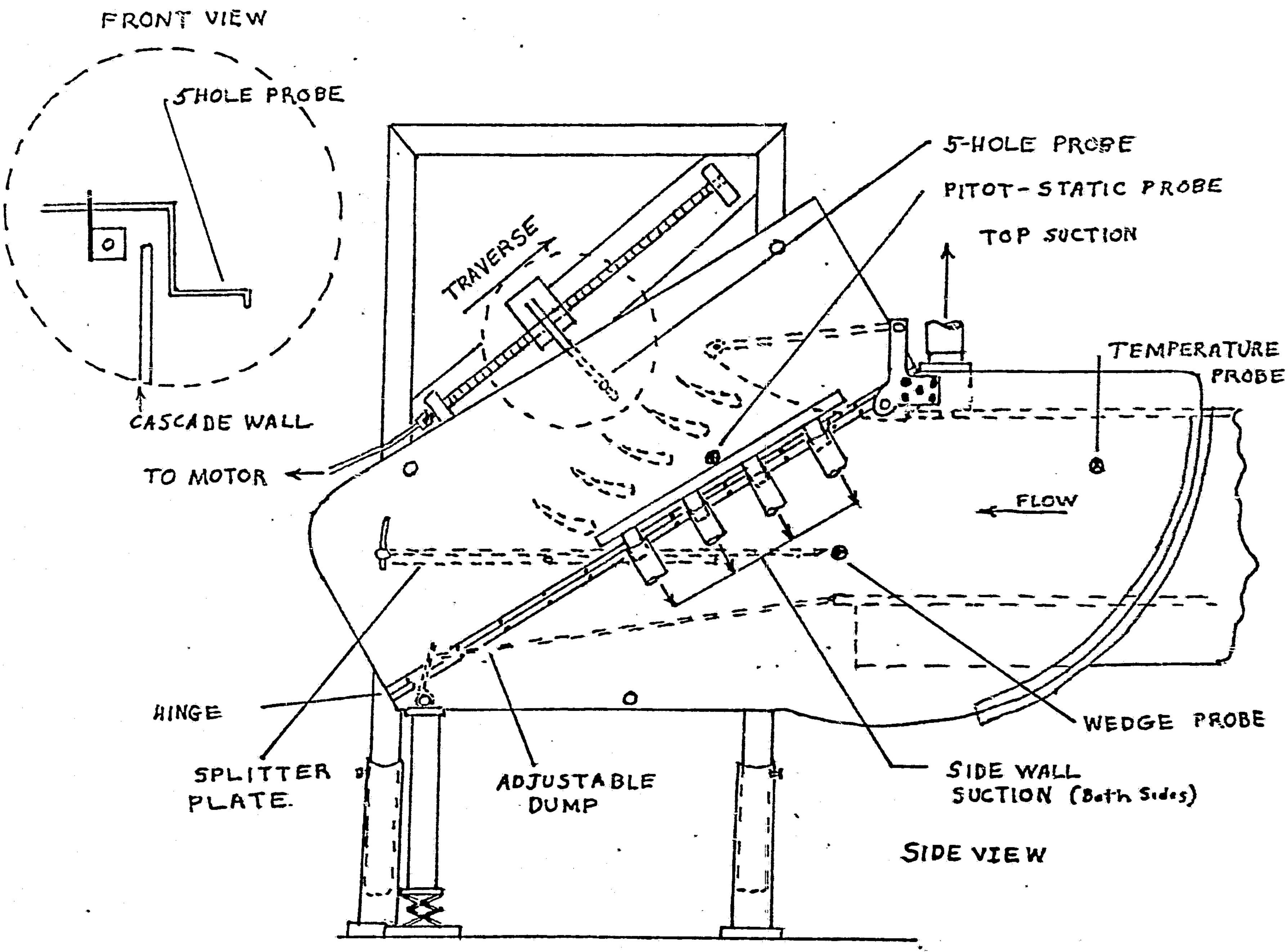


Figure 2: Cascade Facility

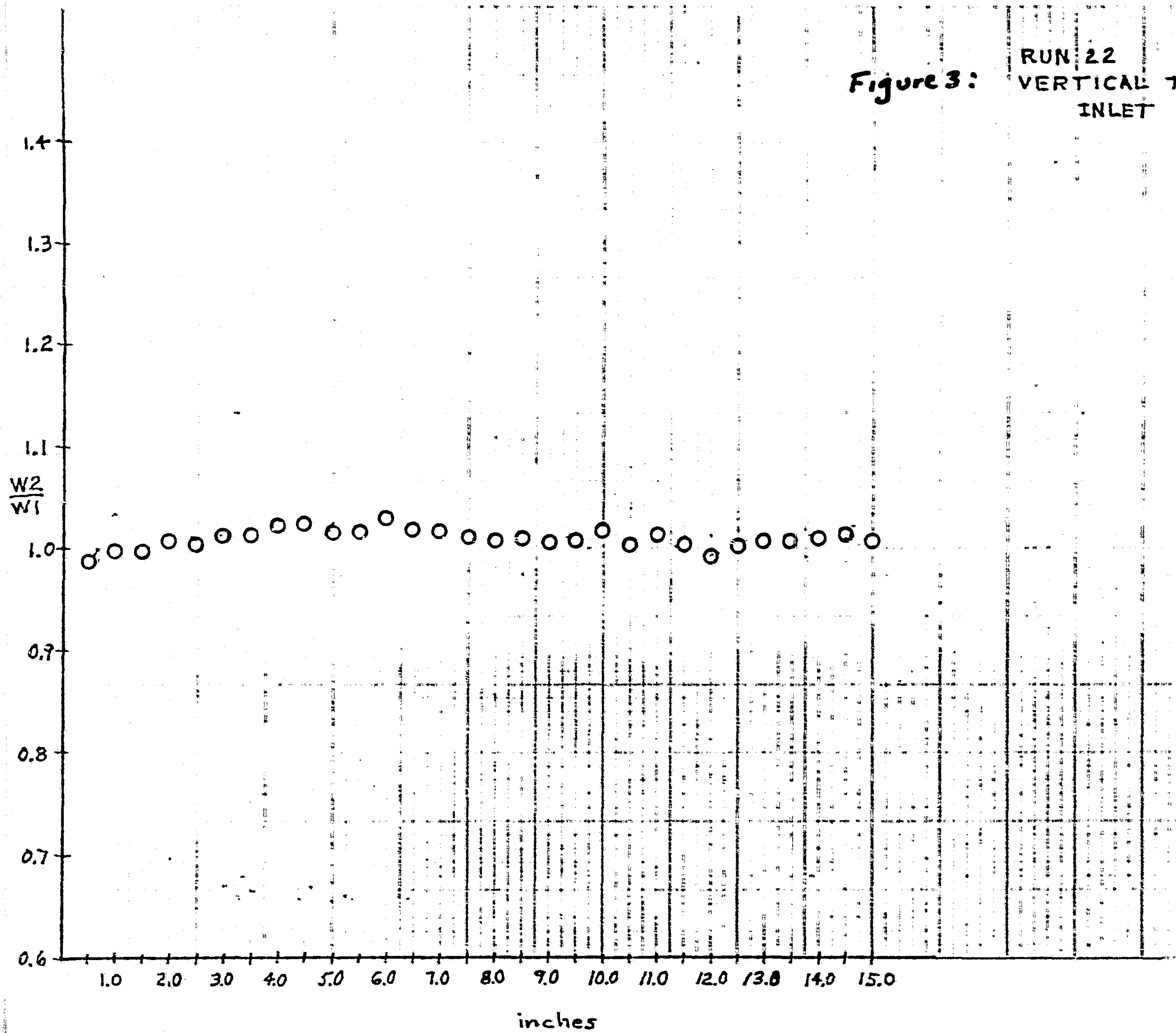


Figure 3: RUN 22
VERTICAL TRAVERSE OF INLET FLOW

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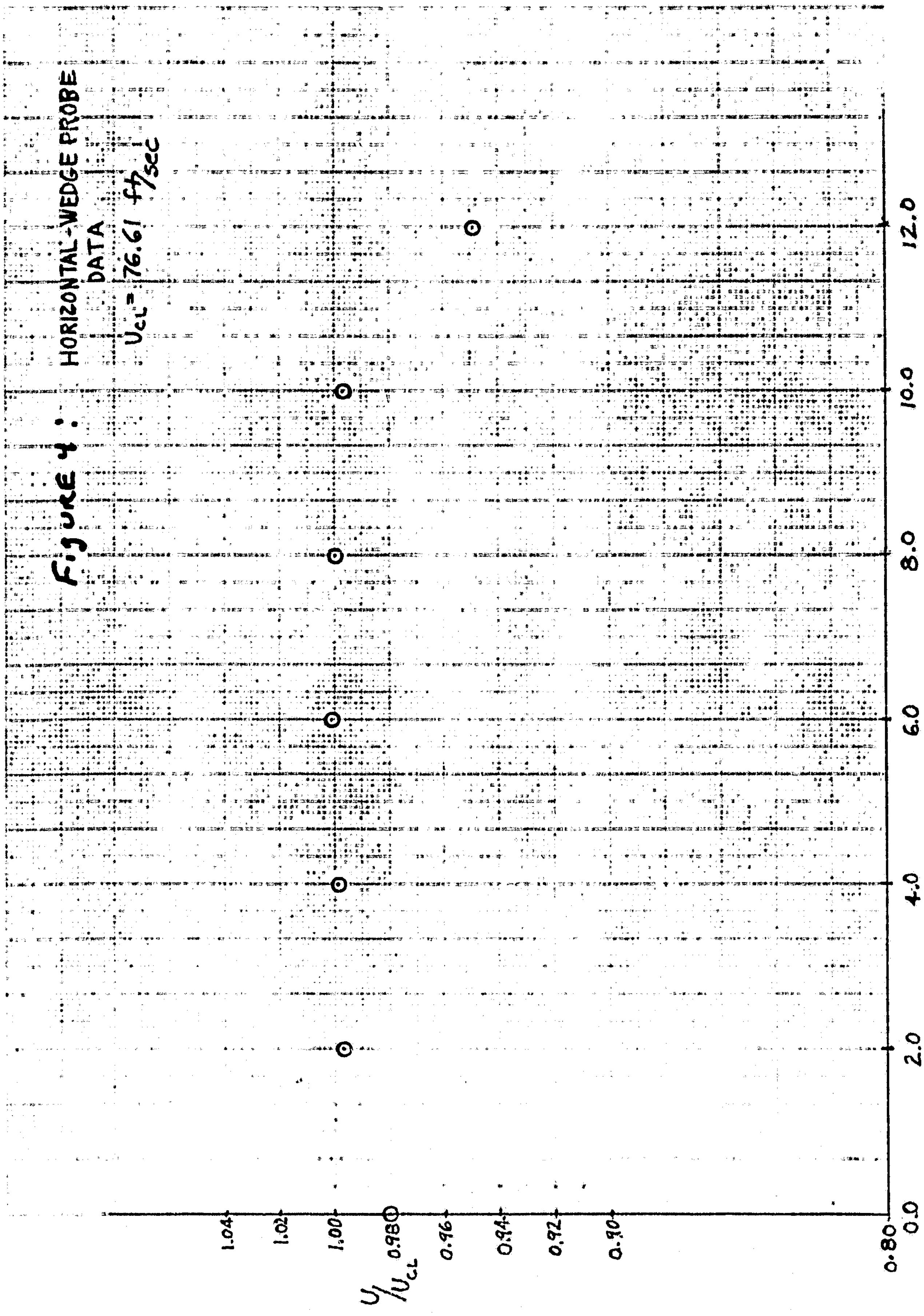

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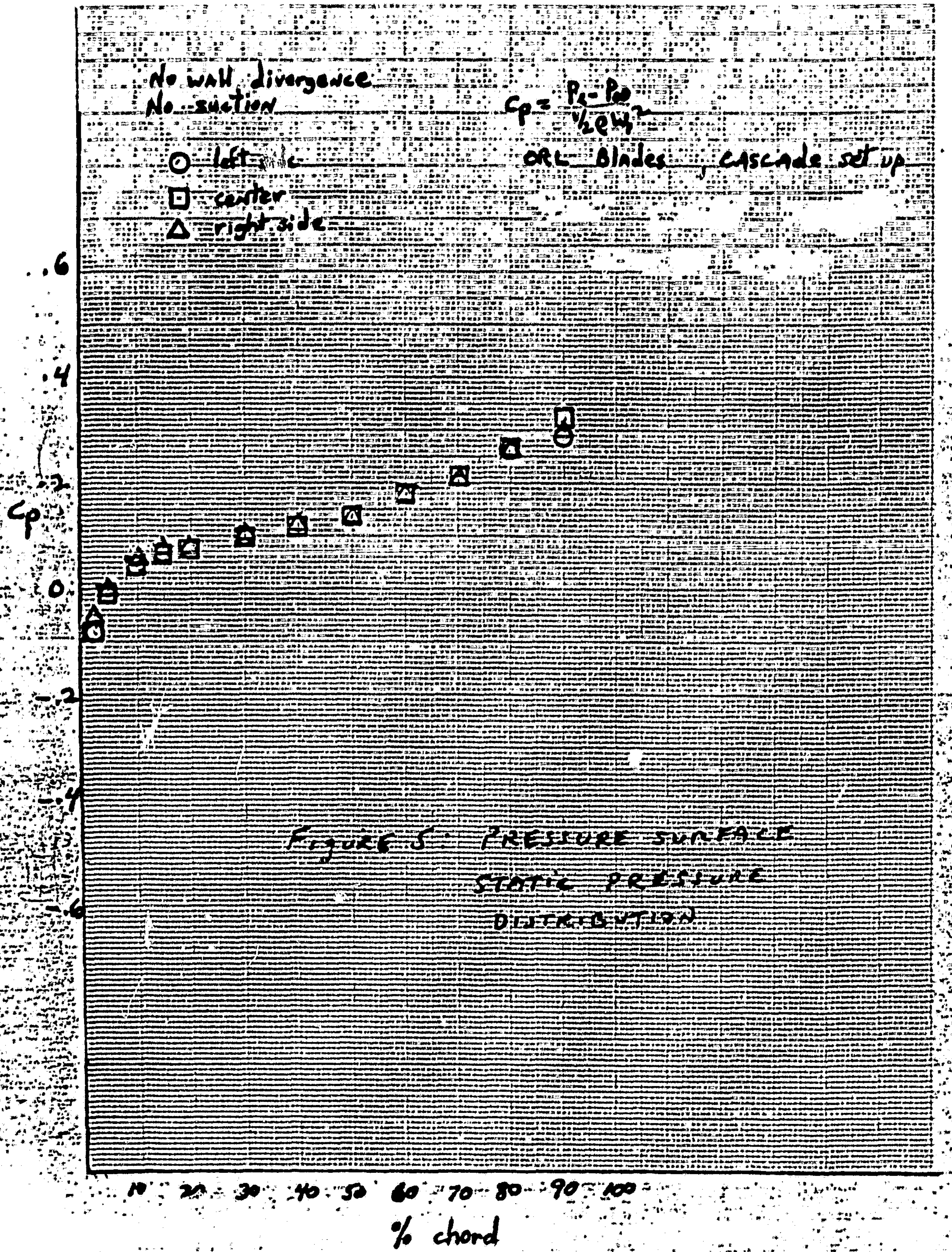

FIGURE 5: PRESSURE SURFACE STATIC PRESSURE DISTRIBUTION

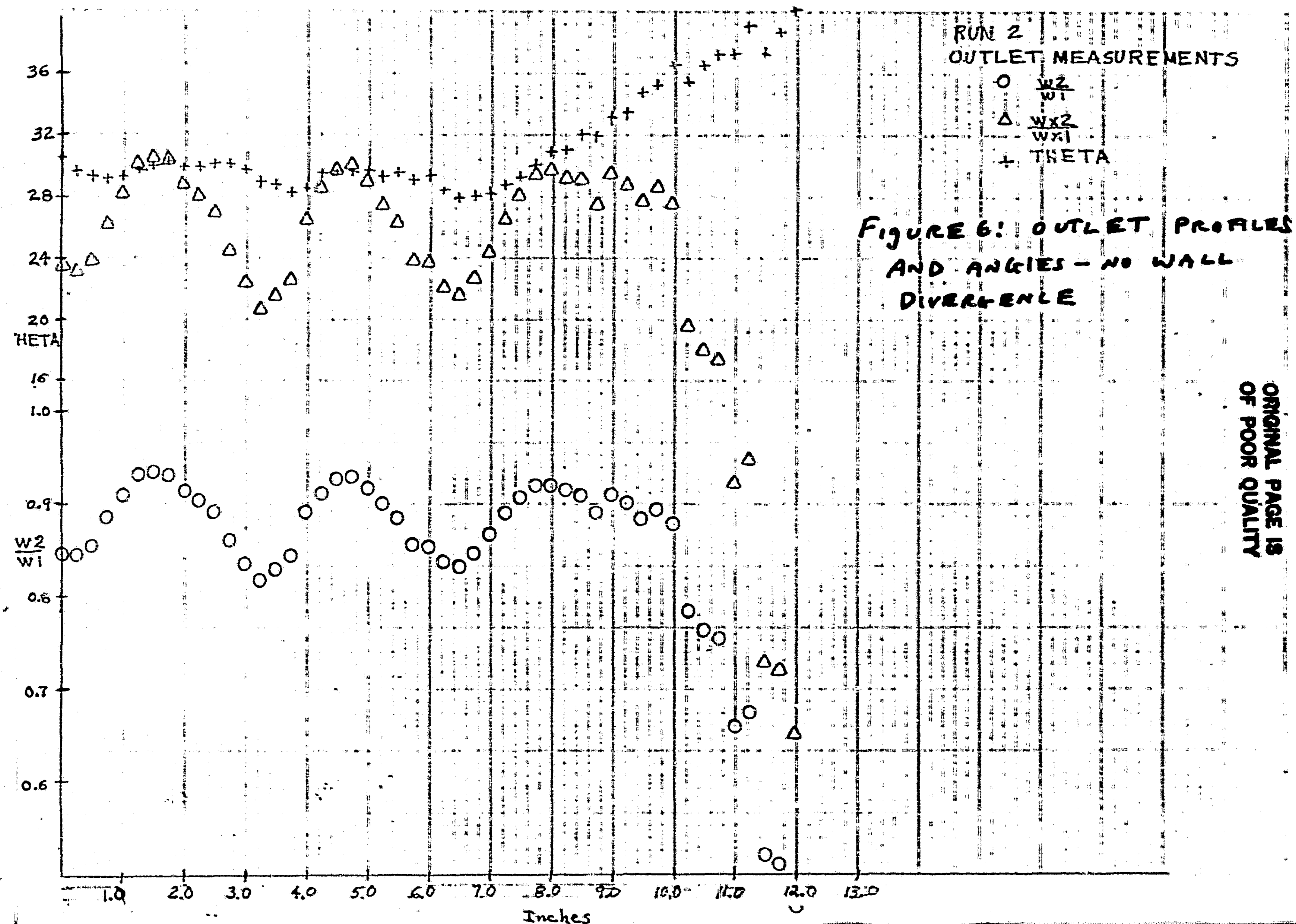

FIGURE 6: OUTLET PROFILES AND ANGLES – NO WALL DIVERGENCE

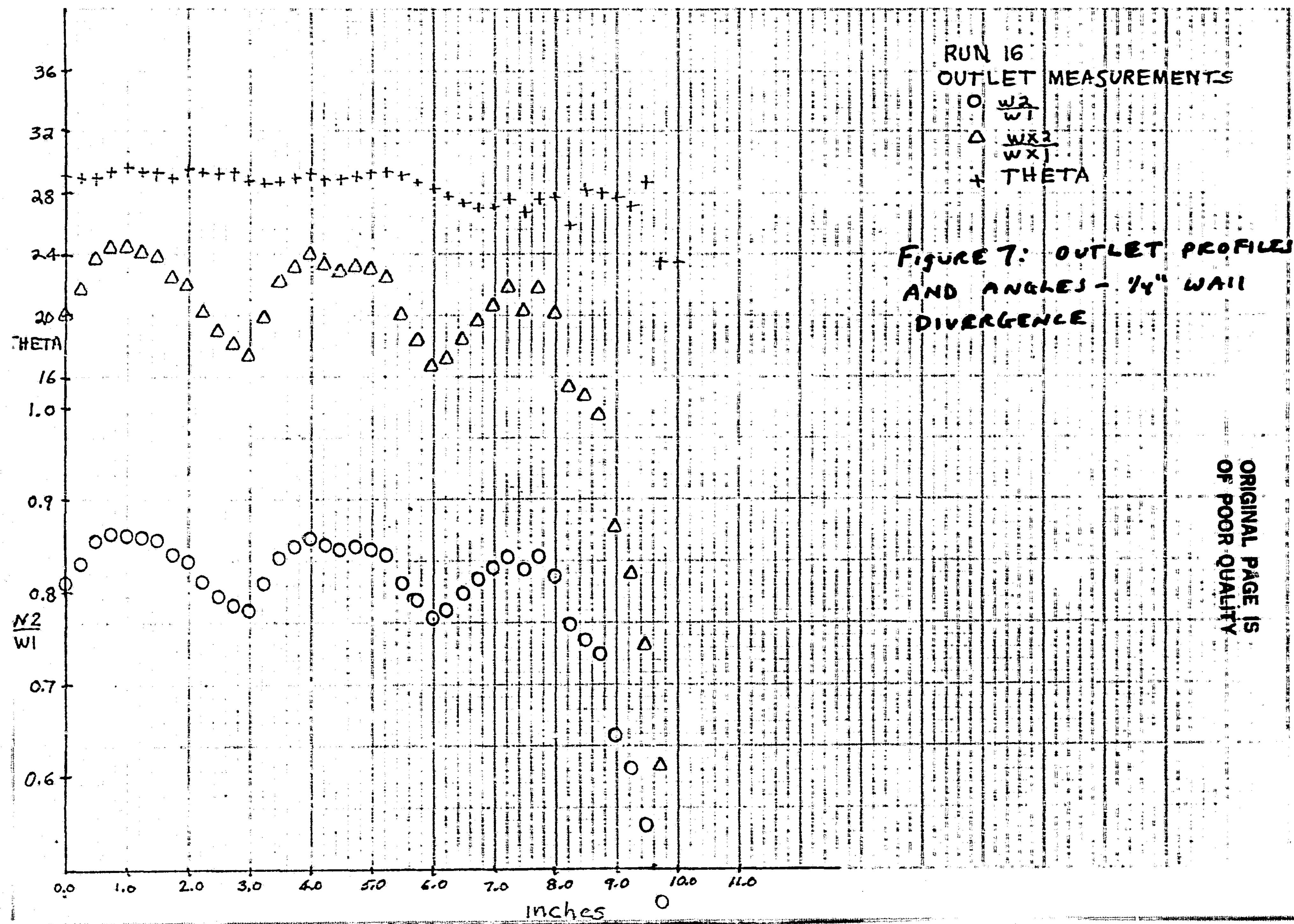

FIGURE 7: OUTLET PROFILES AND ANGLES - 1/4" WALL DIVERGENCE

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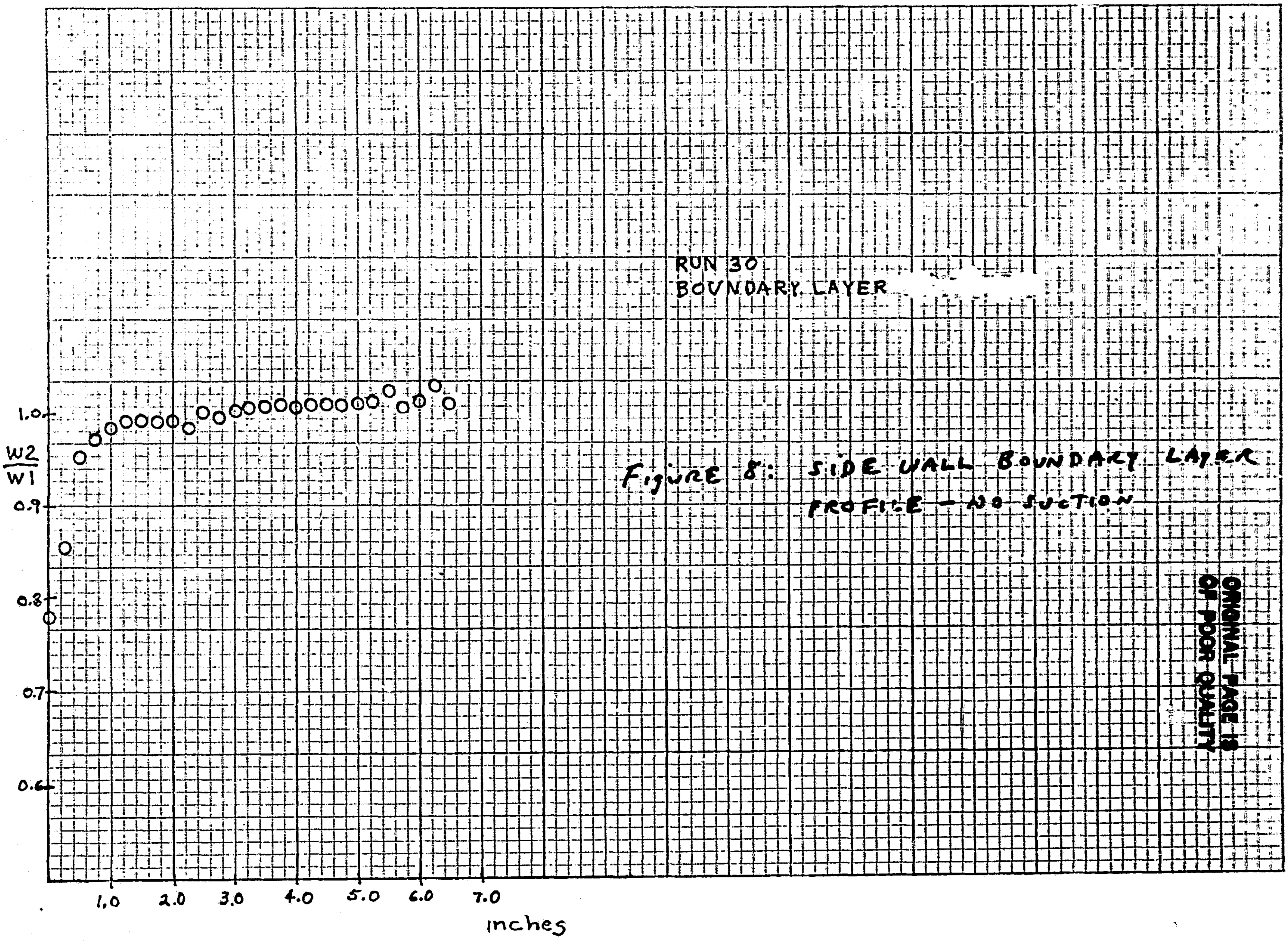

Figure 8: SIDE WALL BOUNDARY LAYER PROFILE — NO SUCTION

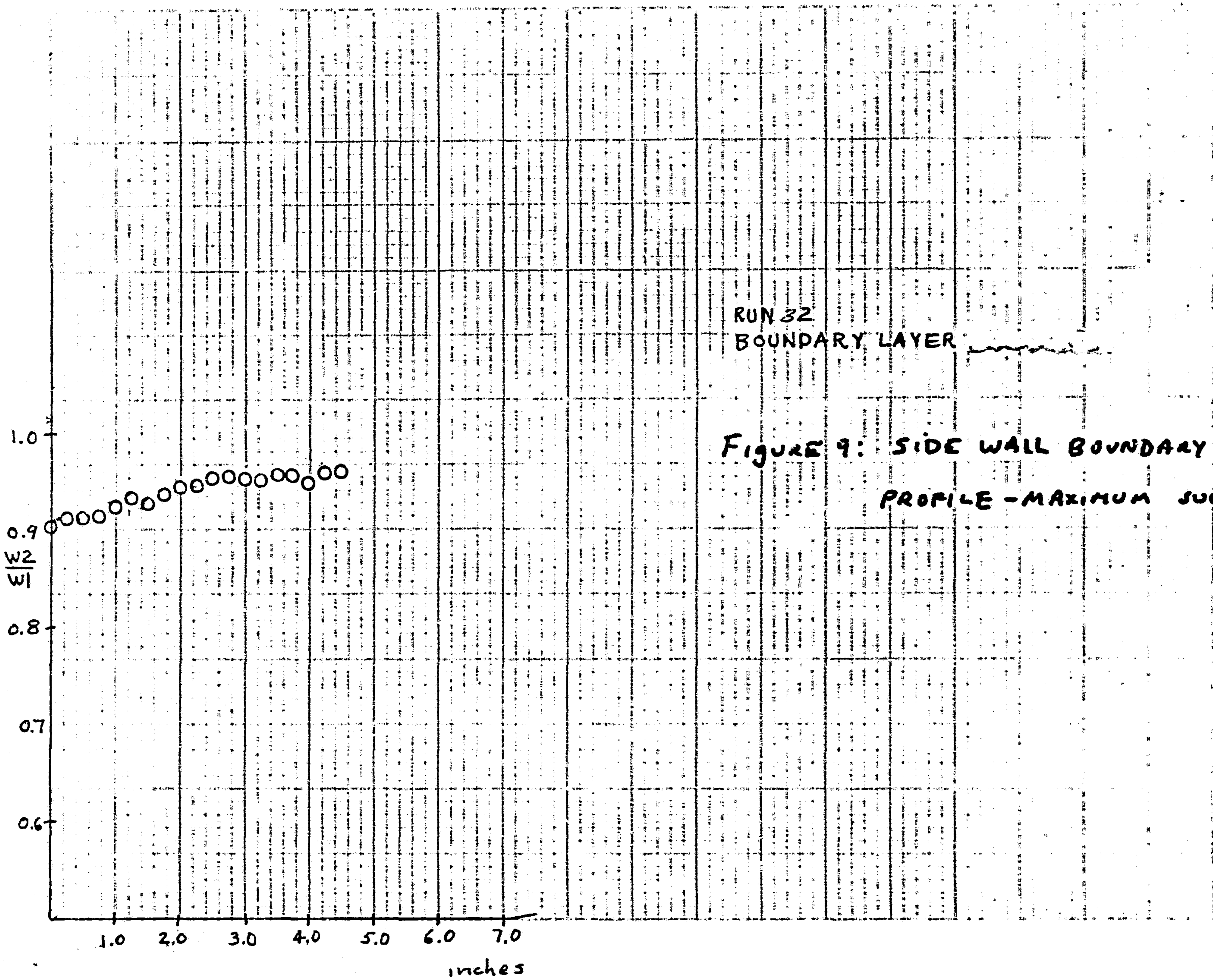

Figure 9: SIDE WALL BOUNDARY LAYER PROFILE - MAXIMUM SUCTION

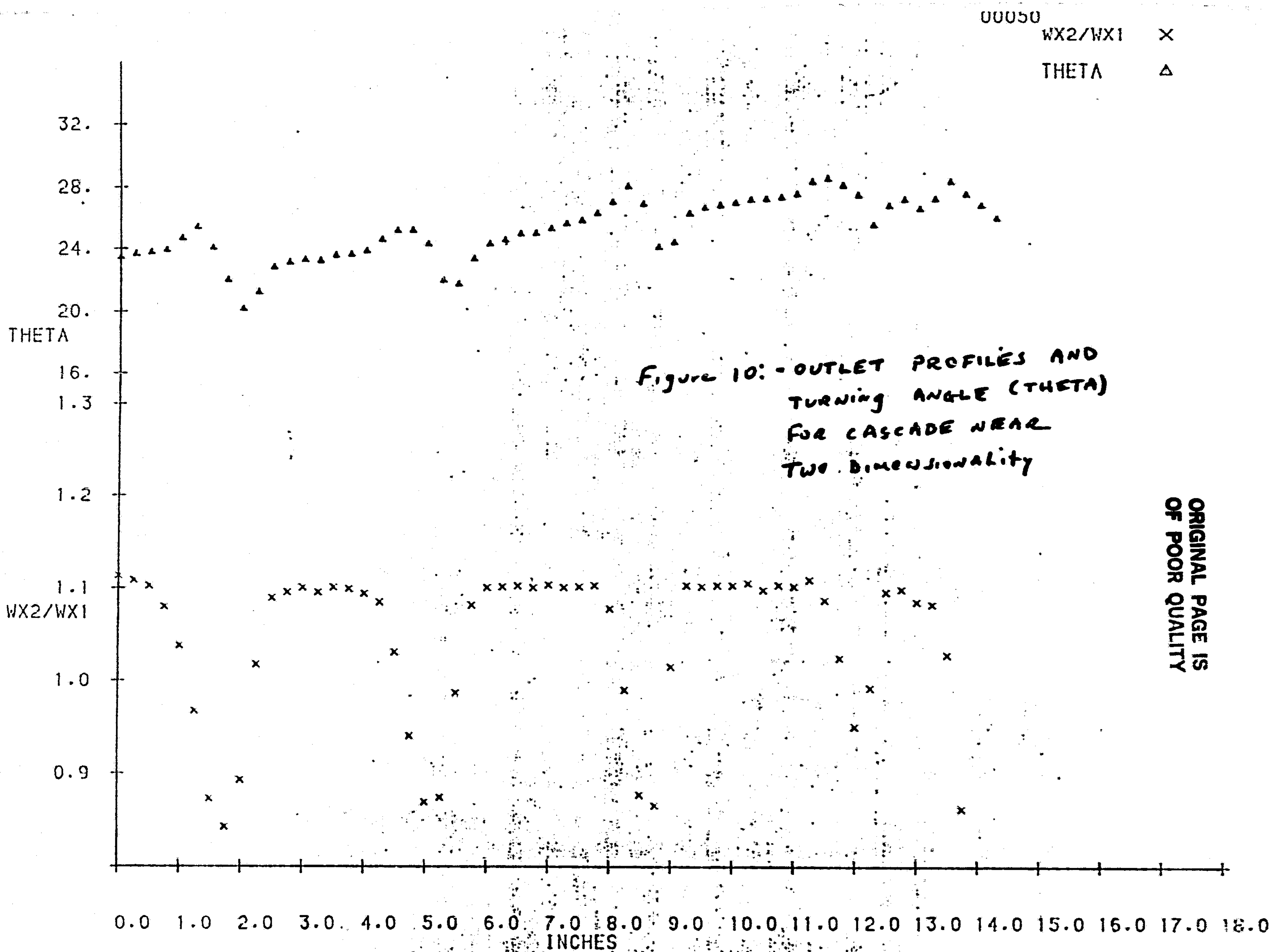

Figure 10: - OUTLET PROFILES AND TURNING ANGLE (THETA) FOR CASCADE NEAR TWO DIMENSIONALITY

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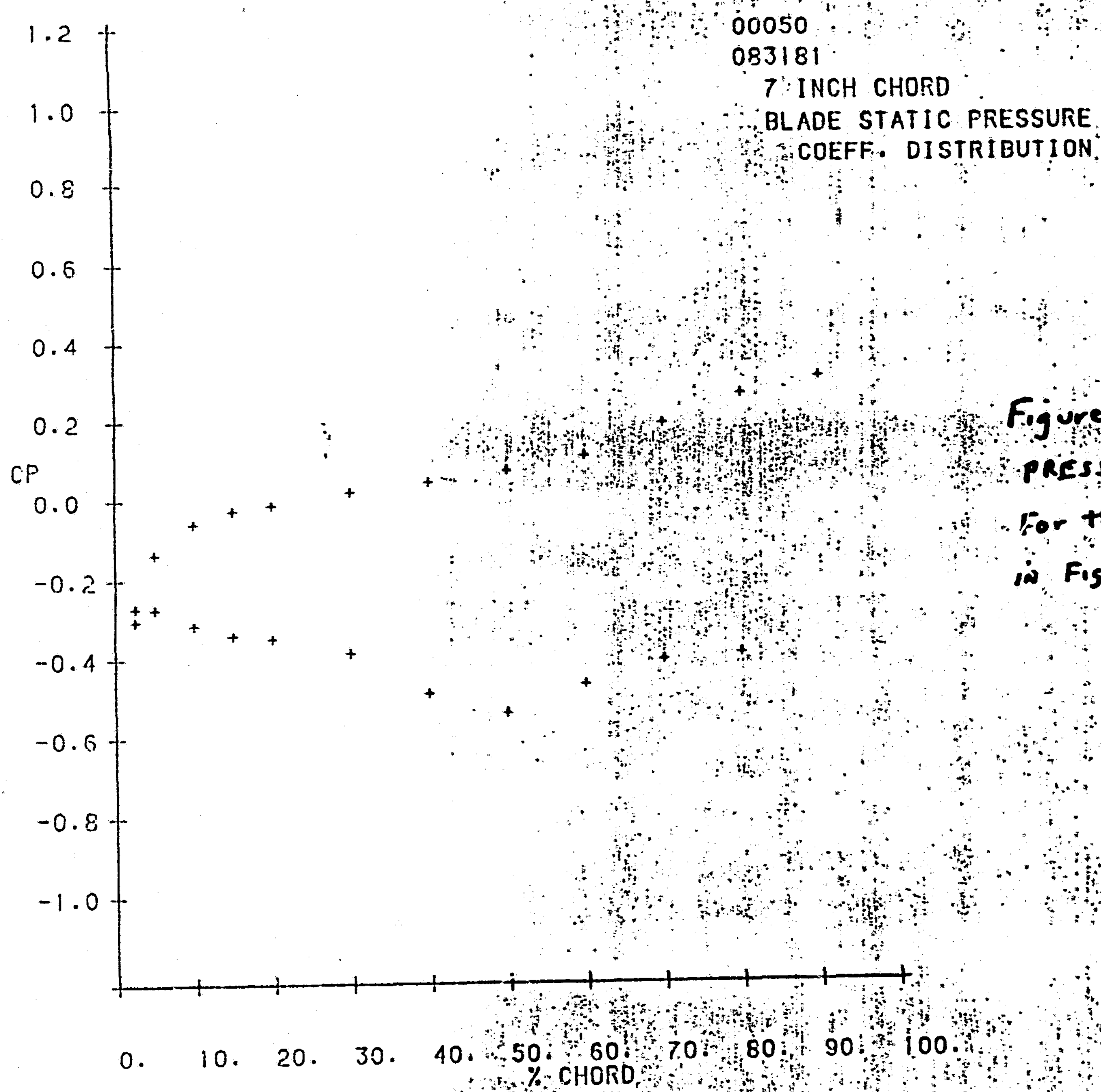

Figure 11: Blade static pressure distribution for the case presented in Figure 10.

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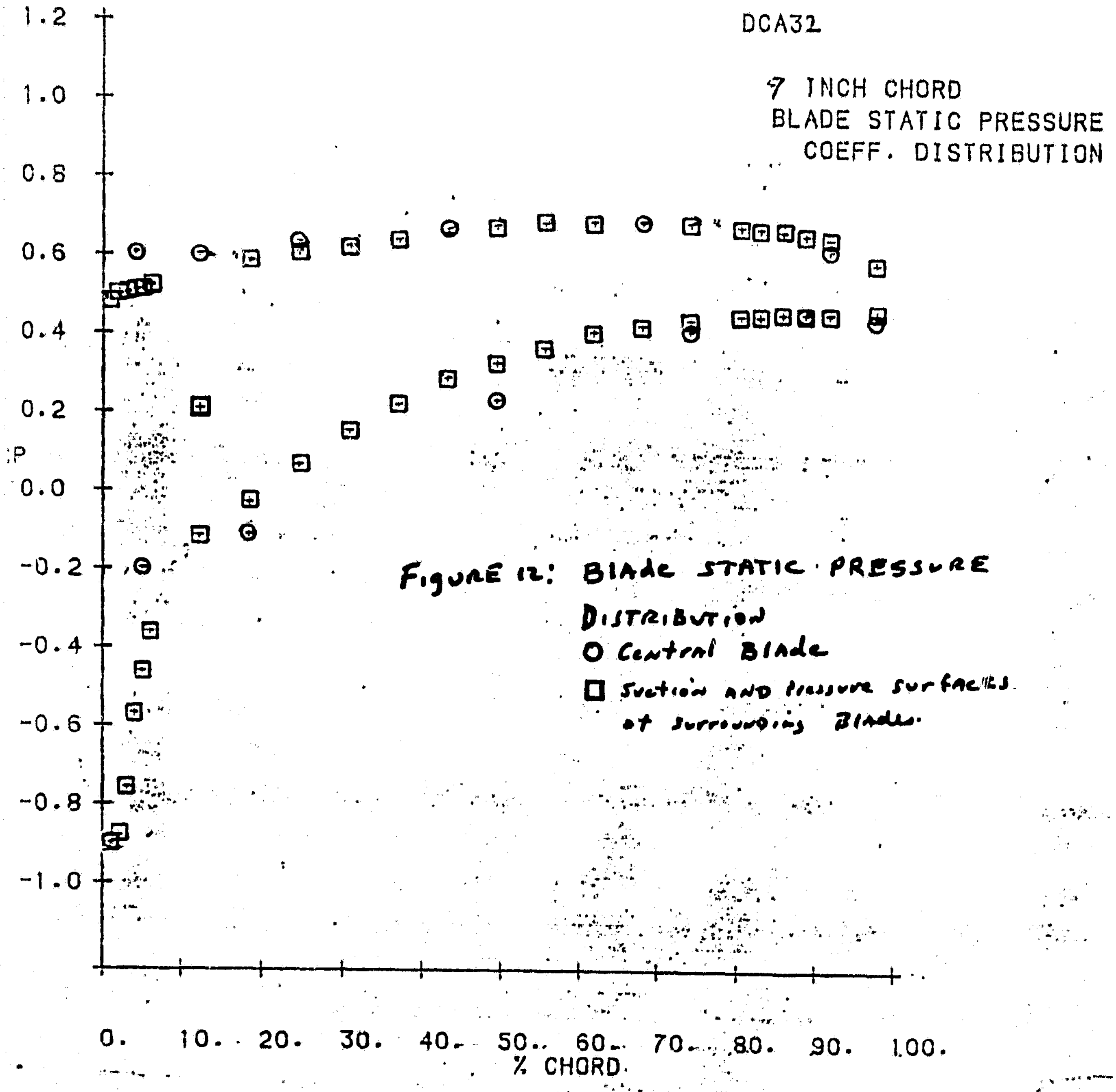

Figure 12: Blade Static Pressure Distribution
○ Central Blade
□ Suction and Pressure surfaces at surrounding Blades.